TRENDS IN MACHINE TOOL DESIGN.

Paper presented to the Institution, Birmingham Section, by I. H. Wright, M.I.Mech.E., M.I.P.E.

IN reviewing the developments which have occurred in the design of machine tools during the last ten or fifteen years, one sees that these generally represent the effect of trends imposed either by the needs of the user, or by competition between machine tool makers, and their efforts to keep their machines abreast of modern shop practice.

The former class naturally is the more interesting, as the acceptance of any development by a circle of users not only represents real progress, but also because it is based upon collaboration, direct or indirect, between user and maker. Also, in this class the members of our Institution can feel a personal interest, as many successful developments are found to be the result of collaboration between the production engineer who is ultimately to use the machine tool, and the maker who is anxious that the machine shall meet all reasonable requirements when installed.

In these cases it will occasionally be found that the production engineer has formulated a list of requirements and a record of previous results and data; discussed the matter openly with the machine tool maker; and later accepted a scheme embodying the knowledge and experience of the machine tool maker, and neither of the parties pushing too far into the special field of the other. It should also be remarked that the success of a machine resulting from such collaboration depends upon the friendly acceptance of those who are to use it, and who naturally need to become accustomed to the novel features or combinations.

Though the preceding may suggest some very special and novel machine, it must be emphasised that the same collaboration is very desirable in every possible case, including those where standard or semi-standard machines are purchased ready-equipped for a definite range of work.

In the second class referred to, progress is not always so direct, but it is important because it shows that machine tool makers are, on their own initiative, continually trying to make progress, and insofar as these developments incorporate the builder's experience in his own branch of machine tool work, obtained in many different factories, and on a wide range of work, they are usually worth careful examination, not only because they embody a wide experience, but also because they can be produced in larger numbers,

November 15th, 1933 (Vol. XIII, No. 3, March, 1934).

with consequent economy in cost, as compared with a machine specially developed by discussion between two parties interested in the production of a certain piece.

It must also be admitted that developments during recent years have been greatly influenced by the requirements of the automobile trade, which has constituted practically the only field of demand, and though this field includes a great variety of operations, there is a feeling that development is often somewhat one-sided, and that the classes of machines outside this field are lagging behind; there are, of course, exceptions to this, such as locomotive and railway machine tools, and machines used in heavy oil engine building.

Prophecies Not Fulfilled.

Referring to the prophecy of five or six years ago that special single purpose machine tools would go out of fashion, this has not been realised very fully; the quantities produced in automobile shops still make it often worth while to use machines of a very narrow range of adaptability, though it must be admitted that the greatest development has occurred in the semi-special class of machine tools, which can be used over a moderate range of similar parts by changes in setting and equipment.

The suggestion that the jigs, fixture, and tooling equipment should constitute the essential part, and that the machine tools should provide only the rotation and feeding of the tools, and themselves not require to be of extreme accuracy, does not appear to have been generally adopted. In view of the accuracy nowadays demanded, everything concerned must be as good as possible, both equipment and machine tool.

The Unit Machine Tool.

The unit machine tool proposed by Taylor and others many years ago has begun to materialise in certain directions; for example, many multi-drilling machines now consist of standard units arranged at various angles and positions round the work, each unit being complete as to drive and feed cycle. Often such units are set round an indexing table with one open loading station, the various units either performing a sequence of operations on one centre, or several operations at various centres on the piece. In the milling field some similar development has occurred, but not nearly so much as in drilling. Speaking generally, it is found desirable in such assemblies to have a number of sizes of units available from which to select; too small a number of sizes leading often to undesirable arrangements. In all such machines the units, though each complete in itself, are coupled to start simultaneously, and are interlocked for safety with the indexing table. This simultaneous starting of all units is often done by compressed air

connections controlled by a single valve and lever, or by connecting the various motors to one common controller, with push-button starting and a separate button central to each unit being also provided for manipulation during setting-up.

Effect of New Processes and Cutting Materials.

One of the most fruitful causes of rapid development in machine tools is the introduction of new materials and processes, and new cutting materials, and in this respect, recent years have been very prolific. Developments in light alloys enabling higher cutting speeds, and also cutting materials enabling higher cutting speeds on ordinary materials, have all tended to a general demand for machines suitable for higher speeds.

The speeds involved in the use of high speed steel have been met fairly well by the developments of machine tools during the last thirty years, but the new materials present quite different problems, some occurring at the cutting point, and others in the elements of the machine tool itself. By the first I mean the problems related to the suitable support of the cutting tool, and would suggest here that as the new cutting materials have some physical similarity to the old carbon steels, the technique of the machinist of thirty or more years ago might provide some useful pointers.

By the second class of problem I refer to the necessary changes in design of details to ensure satisfactory and reasonably cool operation at these higher modern speeds. In certain classes it has been found possible to arrange that a slight change in building will make the machine suitable for work requiring a general high speed range, a medium range, or a low speed range.

One of the difficulties of the transition period is that it is often desired that a machine should be suitable for using either high speed steel, or the newer cutting materials as later circumstances shall decide. This involves not only a much wider speed range, but essentially different proportions of the machine details, as in the one case slow speeds with medium cuts require substantial detail and bearings, whilst high speeds with small cuts require smaller detail and different types of bearings.

It is not yet clear whether machine tools which will safely give the high speeds now demanded and also be quite suitable for use of moderate speeds with high speed steel will be developed, or whether it will be better in some cases to provide separate machines for the effective use of the new cutting materials. In view of the possibility of producing finished work, and avoiding later operations, when correctly using the newer materials, it seems probable that a separate class will arise as above outlined.

The multi-tool lathe is an example of the revival on certain lines of a machine not previously greatly favoured, but of which several

interesting designs are now on the market. When the handling of the new cutting materials has been more completely mastered, this type of machine will probably make more rapid progress. The setting of machines with their axis vertical instead of horizontal, with the object of saving space, had made very little progress, and it is disputable if the saving of space has justified the change.

Having presented this general review of the subject, it will perhaps be better for purposes of discussion to examine recent developments in each of the chief elements of design separately, with examples illustrating modern practice. I therefore propose to divide the subject under the following heads:

1.—*Convenience, and time and effort saving.* 2.—*Accuracy and durability.* 3.—*Spindles, bearings, and gear boxes.* 4.—*Casting design.* 5.—*Lubrication.* 6.—*Motor drives.* 7.—*Hydraulic feeds.* The treatment will necessarily be very incomplete, as each of these sub-headings contains enough material for a full paper.

Convenience, and Time and Effort Saving.

With increased numbers of pieces to be produced, the specia tooling used generally throws into strong relief the unproductive times required for changing work and operating the machine. This has caused much greater attention to be paid to all the elements which go to build this unproductive time, the result being visible in a centralisation of machine controls, and often a reduction of the effort required from the operator. Heavy parts which are required to be often moved through appreciable distances are commonly fitted with some form of quick power traverse, and balanced where necessary.

The repeated operation of a chucking or clamping device constitutes a heavy demand on the operator, the muscular effort often demanding a heavy jerk which is very tiring. Variations in casting dimensions often make mechanical clamping unreliable, and therefore the operation of such devices by a compressed air cylinder has gained general acceptance, the natural operation of an air cylinder providing the final jamming action which is usually desirable. The air cylinder also has a following-up action as the jaws sink with the work, due to the action of cutting forces.

In the more highly organised machines used to-day, it is commonly arranged that the whole cycle of movements shall be started by one simple movement, and that loading shall be made as quick as possible. In many cases, particularly in drilling machines, an open station is provided so that loading can proceed whilst the machine is in operation, thus cutting out loading time and giving a greatly increased output.

In all these automatic cycles, provision should be made for emergency return to clear position, and the necessary safety devices,

slipping clutches, etc., should always be incorporated. A further useful practice is to place a visible ampmeter in the motor circuit, having a maximum current mark, to warn those in charge that the necessity of tool grinding is imminent, so that this interruption can be made at a convenient time. In so far as they are applicable, these principles are nowadays generally recognised in the design of general purpose machines, as well as in the machines specially developed for manufacturing production.

Accuracy and Durability.

Interchangeable production demands an ever-increasing accuracy in the components produced and this must, of course, be provided in the jigs, fixtures, and equipment. The idea that the machine tool need then only be of moderate accuracy has not been accepted. Machine tools must now be built to accuracy tolerances often not at all easy to achieve on such large pieces as those constituting the machine tool. Acceptance of the machine is usually dependent on compliance with the limits set. Whether this is really safe, however, is open to doubt ; such alignment tests are usually made on the cool and unloaded machine ; under the actual working conditions practically all machines are subject to local temperature changes and to considerable forces. For minimum alignment disturbances due to these causes, correctness of principle in the design is of primary importance, and is unfortunately not always easy to realise, often on account of stipulations imposed by convenience, cost and method of operation.

Durability in regard to accuracy is also chiefly a matter of correctness of principle in design, and is usually found to occur along with mechanical efficiency from the power consumption point of view. In fact it may almost be said that the chief interest in power consumption is to use it as an index of efficiency and satisfactory working.

Durability of general machine tool elements has been increased by more liberal proportions and the use of more suitable materials and processes, generally adopted from automobile practice, and greatly improved attention to lubrication, which will be discussed later.

In the manufacturing machine these improvements are quite seasonable, as such machines do not usually contain many redundant parts. On general purpose machines, however, this intensifying of detail design involves much more expense, as all detail must necessarily be suitable for the occasional long run on one simple operation which actually only uses a small proportion of the numerous machine elements. They must, however, all be up to constant duty quality.

The most striking improvement in relation to accuracy and its retention is probably the introduction of improved methods of producing slide surfaces, the protection of slides, and the growing use of hardened and ground slides. Handscraping of slides is often displaced by grinding, the result being a flatter surface with no local depressions, which often form starting points for serious wear. The lubrication of such ground slides is also claimed to be superior to scraped slides.

Protecting of slides, at least of horizontal slides, such as lathe beds, is now a regular practice. One well-known firm fit really substantial stainless steel covers of effective design which have proved of great advantage in reducing wear. Another firm use a cover which actually lies on the surface to be protected, and so prevents not only falling swarf, but also dust from lodging on the slide surface. The "roller blind" type of cover has not been generally adopted; it is fragile and in principle not sound, as it can, and usually does, deposit swarf secondhand on the slides it is nominally protecting.

Spindles, Bearings, and Gear Boxes.

As the spindle in a large proportion of machine tools carries either the work or the cutting tools, it must be designed to transmit the cutting forces by its bearings to the machine frame in such a way as to utilise the stiffness of frame and slides to the full.

Years ago, spindles were of moderate proportions and bearings not very long; with the introduction of high speed steel and its increased strength to take heavier cuts, the spindles were made larger in diameter. It was then found that the close bearing fits necessary for successful lubrication at slow speeds were too close for high speeds, so bearings had to be made with thicker oil film allowance. This also demanded that bearings should be made longer to give load capacity and accuracy with the thicker oil film. Better methods of finishing bearing surfaces were also introduced, so that modern machines for using high speed steel now have very highly developed spindles and bearings.

For the heavier classes of work, using the newer cutting materials, it would appear that these spindles, though their stiffness is an advantage, present bearing difficulties which are still to be overcome if lubricated journals are to be retained. In this field, the use of ball and roller bearings is making good progress, as the heat generated in a close-running ball journal is much less than that of a lubricated journal of equivalent capacity and speed.

Closeness of fit can also be superior to that of a lubricated journal, and where extreme closeness is essential, preloaded ball journals, or taper roller journals which are easily adjusted, are often used. The application and fitting of such bearings is found, however, to

require as much care as the older lubricated bearings. Such spindles often show a tendency to transmit torsional vibrations caused by the natural process of chip-building, and permitted by the torsional elasticity of transmission shafts. This trouble can often be mitigated by the use of a flywheel on the machine spindle.

For the very lightest work, using the new cutting materials, lubricated journals seem to persist, as they undoubtedly have a "silkiness" not found with ball-and-roller bearings. Such cases are still in the experimental stage. In some machines, the difficulty of great speed range requirements is overcome by providing a slip gear arrangement to decide the general field of speeds to suit materials, cutting medium and type of work, together with a reasonable number of lever changes for variations of work and cutter size, and different operations.

For instance, such a machine can have, say, three general ranges; one for very high speed work, one for medium speed, and one for maximum capacity work. This class of machine practically always has anti-friction bearings of some kind, it having been found very difficult to provide lubricated bearings which run satisfactorily over so wide a range of speeds.

For general drive transmission, ball journals are now quite general, as are also alloy steel gears with teeth ground after hardening. Shafts of solid-spline type are also the usual thing, and these of much greater diameter than they were a few years ago. Feed trains and auxiliary mechanisms increasingly use ball journals, but this cannot be said to be general. The location of control levers for speed and feed changes has also been improved, it being often claimed that all control movements can be made from the operator's usual position.

Another element which has been greatly improved is the driving clutch. Multi-plate types are now much more used, and with the frequent operation now demanded, are superior to the earlier expanding or cone type, as the engaging elements offer usually a larger surface, and are of better wear-resisting materials. Usually, also, a much smaller force is required for engaging them.

Casting Design.

It can, I think, be claimed that alongside the various changes in detail design, and the addition of further mechanism for new operations, the general appearance of modern general purpose machines has also been improved.

This is, of course, secondary to the fact that casting design has developed. Box castings, though good from the strength point of view, have been found deficient in rigidity and damping qualities, and have largely been replaced by a cellular type of structure, recent tests having proved that a box member is very much stiffer

if provided with a cellular network of diagonal ribs similar to a W, and this is nowadays largely practised. The presence generally of large flat plates in castings is also undesirable, and these are often divided into smaller panels by light cross-ribbing. This increases the natural vibration periodicity and tends to the damping out of vibration, so that on this account at least, modern machines run more quietly.

Referring also to casting design, it is noticeable nowadays that the natural weakness of the ordinary milling machine of knee and column type is better appreciated, and that an increasing proportion of milling operations is being carried out on machines of the fixed height table type, which are found to produce more accurate work over a larger cutter life between grindings, and also to be much more secure against the occurrence of chatter, a trouble very common on the knee type machine, due to its open frame form.

Coolant tanks are also much more liberal in dimensions, and more accessible for cleaning. In this connection may I suggest that the common nuisance of splashing the operator can often be greatly reduced by using a sufficient volume of coolant *at a low pressure*.

Lubrication.

In the semi-special manufacturing machine, lubrication is an essential part and is usually provided for, but in general purpose machines, it is only in recent years receiving due attention. The number of lubricating systems is considerable and by reason of the circumstances it is usually necessary to use several different systems in a large machine.

In gear boxes and compact mechanisms, for instance, splash lubrication with visible oil level is general. For more straggling mechanisms, transmitting considerable power, a pump circulation and cataract distribution is regular, but where several portions of the mechanism have relative movement, as the saddle of a lathe, each such mechanism must have its own pump system. In such systems it is becoming more usual to fit an oil filter, usually dealing with a fraction of the circulating oil ; though there is no " carbon " in a machine tool, it is surprising what an amount of solid matter such a filter will intercept !

For parts which only move occasionally, and under a small load, a favourite way is the " one shot " system, but unless this is very carefully laid out and fitted, it can be deceptive. It is also desirable to test and check such a system periodically ; broken pipes, stopped regulators, failure of supply on long lines, etc., can cause trouble.

Another, and perhaps more reliable system, is to use a " grease gun," and to place the oiling points in a compact group on each main part of the machine. The use of bearing bushes of self-lubricating materials is also gaining in favour, and for the isolated,

occasionally-moving bearings is found quite satisfactory. But it must be remembered that the best lubricating system is only effective if it receives regular attention and replenishment. It may even be suggested that lubrication is so important and technically so complicated that an expert of the status of an electrician should have it in charge.

As an alkaline coolant is very often used, and as it has hitherto proved impossible to quite prevent ingress of coolant to the oil chambers, only a non-saponifiable mineral oil for lubrication is safe on such machines.

In certain high speed spindles such as in grinding machines and fine boring machines, ball bearings have not usually proved successful, and various special methods of film lubrication have been developed to meet the very exacting conditions, the main feature of these being the continuous supply of a suitable lubricant at the correct point in the bearing. It may be said that these special cases have caused a more fundamental study of lubrication on the part of designers, and have brought improvement in many other instances.

Motor Drives.

Countershaft and cone-drive machines can be regarded as obsolete in most cases. The single-pulley machine is still in a majority, but for special manufacturing machines, the independent motor drive is quite established. In general purpose machines, the single-pulley is the fundamental standard, with the possibility of motor driving on to the single pulley.

The considerable use in England of direct current, and the great variety of motor designs, have so far prevented the development of really neat and compact motor drives on general purpose machines, and in so doing have prevented such a cheapening of this feature as would have made it much more general in recent years. The approaching general change-over to a national standard A.C. is already having an influence in this direction, and American and Continental practices in the way of incorporated motor drive are beginning to be seen in English machine tools.

The simplicity and reliability of the squirrel-cage motor for small powers, together with its cheapness and simplicity of control, have encouraged the use of multiple motors as a substitution for straggling mechanical transmission between the various units of a composite machine, and for auxiliary movements.

The item of an electric coolant pump, though small, is a very appreciable improvement, and cuts out a lot of trouble. The use of pole-changing motors is also gaining ground. They may have such a range of speeds as to enable either a great simplification of gear change mechanism, or the provision of much closer steps in

the gear changes, making more exact speeds available. For high speed mechanisms which require frequent reversal, such as tapping machines, the squirrel-cage motor, by its ease of reversal and absence of shock, is greatly superior to most forms of clutch reversal. Now that a hycycle standard is in general use of 100 v. 200 three-phase, much higher speeds are available, and small grinder and drill spindles may be direct motor driven.

The use of the generally neater flanged type of motor is often resisted on the grounds that it is not interchangeable, in case of emergency, with standard machines. This reason applies only to the stator windings ; generally a standard stator could be used as replace until the coils are rewound. This particular reason for resistance to flanged motors is, however, supported by the continued use of D.C., and varied design motors, and, if it were removed, would at the present time still leave sufficient inconvenience to prevent their general adoption as a basis of design.

Hydraulic Feeds.

This constitutes a new technique introduced into machine tool design. In fact, the methods used differ so much from traditional hydraulic practice that one might claim that it is quite new generally. Its main advantages are that considerable changes in velocity of the body moved can be made without shocks, and with greater convenience and less effort than when these changes are made mechanically. Remote control is simpler, and the force produced can be controlled by a simple spring-loaded relief valve. Its disadvantages are that the rate of movement produced is not precise and constant, being dependent on valve and piston leakage, and variations in viscosity due to temperature, and that the oil and piping system have an appreciable volumetric elasticity.

In the field of grinding machines and of drilling and boring machines, hydraulic feeds have already become established, also as auxiliary service on some other machines. In these cases the nature of the hydraulic movement is quite suitable, though variations in rate of movement due to viscosity and temperature changes are sometimes a disadvantage.

In many of these applications, the movement is produced by a cylinder served by a gear type pump running at constant speed, the rate of travel being controlled by a throttle valve in the line to cylinder, or in some cases in the line exhausting the idle end of cylinder ; in either case the rate of motion on starting up cold is much slower than that obtaining after the oil has warmed up to its working temperature.

This method of moving a slide is also advantageous where the length of traverse must be exact, such as in grinding and in slot

drilling operations, using a small and overhung cutter. The Craven Slot-Hydromill being a good example of this. In this machine the slide moves against a dead stop, and the building up of pressure actuates the reverse valve.

In heavier duty machines, and where a more definite rate is desired, a variable delivery pump is used instead of a gear type pump. This, however, is still not quite constant, as piston leakage increases with temperature, and rate of movement consequently falls off.

It has been found desirable generally in these machines to keep an appreciable pressure even on the exhaust line. This prevents the sucking in of air at glands and joints, and minimises the cushion effects of any air which may get in with the oil. Air leaks, or " bleeders " are usually fitted at high points of the system, to allow a constant leakage of oil and entrained air.

In the milling machine field only one firm has made any serious attempts to use hydraulic feeds, though they have had considerable success where the machines are used mainly for face milling operations, as the feed here is rather similar to that of a drilling or boring machine, for which hydraulic feed is very suitable.

On slab milling with cutters mounted upon an arbour, however, the hydraulic feed machine presents great peculiarities, in that the table and work reciprocate slightly instead of feeding steadily forward. This is often objected to at first sight by users, but the makers of the machine claim that this action is favourable to cutter life, and therefore an advantage. It is found that this reciprocation in some cases causes wear of the slides.

Variable speed rotary transmission by hydraulic means has been known for a long time, and in two or three cases has been applied to machine tools, but these have not been long enough in general use to be regarded as acceptable. An important quality of hydraulic transmission in such connection is the absence of steadying " flywheel " effect which is present with gear transmission.

In machines where accuracy of movement is important, the members constituting the hydraulic system must be kept clear of the important members of the machine; otherwise temperature variations will cause disturbance of the machine's accuracy.

In conclusion, may I suggest that the present practice in the use of modern high speed steel, and our lack of knowledge of the best methods of using the new cutting materials, present a field for research quite as wide and quite as important as the early researches made in connection with high speed steel, but that such research should cover the field of commercially economical cuts and modern materials, and not the removing of uneconomically heavy chips.

Such research should include not only cutter shape, but method of supporting and other factors present in the application of a cutting material.

I wish to thank the following firms for the loan of slides and data: Messrs. James Archdale & Co. Ltd.; Craven Bros., Ltd.; Alfred Herbert, Ltd.; B.S.A., Ltd.; and H. W. Ward & Co. Ltd.

Discussion.

Mr. E. W. Field (Section President) said that the first point which had struck him had been the lecturer's very commonsense attitude on co-operation between ultimate user and designer. Speaking strictly from the machine tool maker's point of view, problems were often thrown at them without any help at all, and their resultant efforts were criticised with the statement, "We thought of that years ago." The question of creating special machines for the use of the high speed steel type of material, and other special machines for the tungsten carbide material, was hardly a practical proposition, and most makers, so far as he could gather, were proceeding on the lines which Mr. Wright had indicated, by building machines capable of running at high or low speeds to suit the material.

From the theoretical point of view, Mr. Wright would tell them that spindles could not be made for both, but as machine tools were never made in the right way anyhow, we should not worry unduly about that.

Another serious problem was that of change-pole motors in which Mr. Wright had referred towards the end of his paper. It was a problem which electrical people ought to take up, and they could help the machine tool maker considerable by giving him pole-change motors with a rather wider range of speeds than the present A.C. current allowed. It was rather a drawback to the motorised spindle machine because it did not cover certain operations such as screwing. Mr. Wright had rather slurred over the question of saving the operator fatigue, and this was a point on which designers at the moment were concentrating, and, it was hoped, would continue to concentrate.

He was rather surprised that Mr. Wright had not given them an illustration of a heavy machine with an in-built crane. It seemed to him rather wrong, in a shop of the heavy machine type where there were 40 or 50 machines, that they should depend on one or two shop cranes for the whole of the machines. In one or two shops of the modern layout type, jibs were provided swinging from the ceiling, and serving several machines. As a matter of fact, the speaker had that day been discussing with a certain gentleman the advisability of putting in a radial drilling machine with four work tables, and this gentleman had suggested that while its operator had the crane he might have four lots of work put up at once, and save waiting time. It was true that in a number of shops workmen were kept waiting for the crane, and the built-in crane might cut out this idle time. Another point which Mr. Wright had not dealt with to any great extent was the question of swarf di. posal. This was a

point which was exercising the minds of a tremendous number of machine tool designers with varying results. Perhaps Mr. Wright had left it out because he could not give it any word of praise ?

MR. WRIGHT said that the point of co-operation was one he had mentioned many times as opportunity had arisen, and people who were interested in the development of machine tools could do their little bit in many ways to encourage this co-operation between the people who wanted, and the people who were to make the machine, by laying their cards on the table, and giving the designer a proper opportunity of meeting their requirements. On the subject of pole-change motors and range of feeds, perhaps Mr. Groocock might have something to say, but on drilling machines what he would advise, in machines with the motor direct on the spindle, would be, "Have all possible speeds." With A.C. current, however, the number was pretty well fixed. He was very much obliged to Mr. Field for having suggested operator's fatigue. It had been quite an omission on his own part not to refer to the necessity of cranes on machines by which work delivered on a truck to the machine could be lifted on to the machine without waiting on the shop crane.

On the question of swarf disposal, he was concerned to some extent with drilling, and swarf disposal in drilling, if they could only get it to start at the drill point, would be a wonderful thing. It was bad enough after it got away from the point ! He had heard a lot of talk about swarf disposal, and it had been suggested that if, on an ordinary turning operation, a chip breaker was put on, the broken up chips could be disposed of very much more easily, but the people who were making all the noise about swarf disposal would not pay extra for the power involved for chip breaking, and the speaker had no sympathy with people who took that attitude.

MR. J. H. FLETCHER confirmed all Mr. Wright had said abou hydraulic feeds on grinding machines, and mentioned the grinding of crankshafts as illustrating the advances made. The time saved as compared with hand grinding the grinding wheel back from the pin after grinding a diameter enabled two extra crankshafts to be ground. Another point was the development of high speed, three speed grinding machines, motor driven. The practice there was to put a three diameter cone on the machine spindle, each driven by a separate Texrope drive. One machine had a very ingenious contrivance fitted so that as the wheel diameter became worn down, it automatically increased the speed. The speed could not be increased until the wheel was worn down to that diameter. This, of course, could not be fitted to general machine tools such as Mr. Wright had been talking of, but it was worth pointing out. The feature of it was that it was impossible for the operator to overspeed ; he could underspeed, but as soon as the wheel wore

down to a given diameter there was a signal for him to increase the speed, and it was claimed that approximately one-third of any one grinding wheel could be saved by that method.

MR. WRIGHT said that he personally had not had very much contact with grinding machines and had therefore not given them attention. The ingenious contrivance mentioned by Mr. Fletcher gave him the opportunity of pointing out that the development of grinding machines during the past ten years had made very rapid progress, and the interest of makers of grinding machines in the correct use of their machines and their efforts to make it almost impossible to use them incorrectly, as exemplified in the example described by Mr. Fletcher, was a further proof that the machine tool makers were really trying to keep up to date.

MR. FIELD asked Mr. Fletcher to further explain his claim for the great saving by the hydraulic feed, sufficient to enable two extra crankshafts to be ground.

MR. FLETCHER explained that the saving in time by the modern hydraulically-driven wheel traverse, as compared with the time taken ten years ago (i.e., hand winding of traverse), to grind one crankshaft, enabled two extra shafts to be ground.

MR. G. H. WRAY said that whereas Mr. Wright had spoken from the point of view of the manufacturer he would like to speak from the point of view of a user. There was one trend in machine tool design which Mr. Wright had not mentioned, and which had not yet come in this country, and that was the standardisation of a ot of parts in machine tools, and also the accuracy to which machine tools could be manufactured. The speaker remembered about three or four years ago a friend of his in Germany sending him Dr. Schlessinger's book on *Limits and Accuracy*, and the way they could be measured on machine tools, and he asked himself why we could not have such a basis for our machine tools and keep to it, so that when we bought machine tools we knew to what limits of accuracy they had been made? There were one or two firms in this country using the Schlessinger limits, and he thought that the purchaser of machine tools ought to have some guarantee, stating to what limits of accuracy they had been made.

MR. WRIGHT said that on the standardisation of detail, the British Standards Institution, of whose technical committee he happened to be a member, were doing all they could in standardising those elements which the user of machine tools quite commonly bought out; small tools and things of that kind; but on the standardisation of the construction elements of the machine, in any good machine tool maker's business, it would be found that a very considerable degree of standardisation already existed. To expect them to standardise essential parts of machines in collaboration with other firms, he was afraid, was rather visionary for the

time being, though we might attain it when we were all Hitlerised !

With regard to accuracy, it was always possible for the purchaser of a machine tool to specify the tolerances in alignment, and accuracy of the machine which he was buying. Some British firms had been using standard tolerances of alignment in the building of their machines long before the Schlessinger book was published even in Germany, and on comparing their practice with the tolerances stated in the Schlessinger book, it was found that they were in every case as good, and in many cases which were considered to be important, they were working to finer tolerances and limits of accuracy than the Schlessinger list laid down. Of course, the German list was remarkably complete in that it mentioned every kind of machine, woodworking machines, presses and punching presses, and the tolerances of alignment and general accuracy which were clearly stated and standardised methods of measuring these were also indicated. It was really a wonderful book, and he recommended anyone who wished to specify commercially possible degrees of alignment on machine tools to buy the Schlessinger book before he ordered his machine tools, and to specify the tolerances indicated in that book. Very often the purchaser of a machine tool set up tolerances of alignment which were impossible to produce in large machines, in which, the speaker suggested, the use of the Schlessinger book, which had been tested and tried out on all kinds of machines would be really useful, and would give tolerances which were commercially attainable.

Mr. Wray pointed out that if one bought machines in Germany, from firms who were members of the German Machine Tool Makers' Association they would be guaranteed to the Schlessinger limits, whereas if we obtained quotations from firms in this country, their representatives would quite rightly say " You are not comparing the same thing." If the machine tool makers in this country got together, and fixed some standard of limits, we should know that certain firms of tool makers would be in agreement. It was not normally the job of the purchaser to fix the limits of accuracy—it was the manufacturer who should do this.

He had recently sent out an inquiry and he asked the manufacturers to state the tolerances to which the machines would be made, they kindly sent them but they were not easily comparable. He thought in general there ought to be some agreement so that the purchaser should not have to do such an enormous amount of work checking tolerances against one another.

Mr. Wright agreed with Mr. Wray that the Machine Tool Association, representing machine tool users, should get together and issue a similar book to the Schlessinger one, or at any rate publish standards for ordinary types of machines, so that customers

would know what to expect without having to go into scientific points and specify for every machine.

MR. E. P. EDWARDS had not heard Mr. Wright make any reference to the use of nitralloy steel material in the manufacture of high speed spindles, which was rather an important development in the last few years. He did not know whether Mr. Wright had attempted to confine his remarks to British-built tools, but he understood him to say as regards milling operations, that slab-milling had not been particularly successful with hydraulic feed milling machine. In his opinion, this was hardly correct. One machine he had in mind was certainly doing slab-milling machine operations without the reciprocating motion Mr. Wright had referred to.

MR. WRIGHT said that on the subject of nitralloy spindles, it probably depended on the spindles, but the firm with which he was connected had tried nitralloy spindles to some extent, and although they themselves did not distort appreciably in the heat treatment (or nothing to grumble about) if the spindle was one where particular accuracy was required, the little distortion that did occur caused quite a lot of trouble, so that though they kept trying nitralloy spindles under new circumstances, they had not got to the position yet where the nitralloy spindles were regularly used on certain machines. However, developments were moving in that direction. The only really successful hydraulic feed milling machine which he knew of, when he had seen one on slab-milling, did reciprocate. Undoubtedly it was generally proved that the hydraulic feed and its reciprocation were favourable to cutter life. He might admit that the hydraulic feed milling machine had now got over the worst of its difficulties and was coming into a better field.

MR. ALIX asked Mr. Wright to tell them what provision had been made in recent years as to withdrawal marks being left on jobs, especially in turret lathes, bar lathes, and boring machines, because he understood that, using modern tungsten tools, they tended to chip off the top when it stopped and the tool was later withdrawn.

MR. WRIGHT regretted that he could not say anything about withdrawal marks. As the tungsten carbide tool tended to chip when it stopped in the cutter, and left a mark, the only way of avoiding withdrawal marks was to stop the feed and let the cut run out. Perhaps Mr. Field might be able to say something about this.

MR. FIELD thought that the tendency which Mr. Alix had mentioned could largely be overcome by the rigidity of the machine used. As a matter of fact, some of the machines which Mr. Wright had had the temerity to illustrate were so rigid that he could assure

Mr. Alix that if one got a dead jam, it would not chip the tungsten carbide. Most of the breakages of tungsten carbide were taking place on the older types of machine which were not built for using it, and although they might, by a compromise, give the speed range necessary, the remainder of the tool was not built for it. If there was sufficient rigidity to hold the tool tip on to the job, one could dead jam tungsten carbide without chipping it. He had proved that on more than one occasion.

MR. J. W. BERRY referred to Mr. Wright's points on lubrication, and asked that he would amplify his statement as to self-lubricating materials. Was he referring to synthetic resin bearings which were being used in the States, and had he any experience of that type of bearing in machine tools where one could lubricate with water or coolant? Mr. Wright had spoken about tolerances. He had had a rather surprising experience in purchasing a secondhand machine, one of those jobs where the ultimate expenditure on equipment was limited. He went to a well-known machine tool maker, who submitted several machines, amongst them a second-hand tool room lathe with specified tolerances! This was supplied and actually found to be within the limits specified.

MR. WRIGHT, replying to Mr. Berry's query on self-lubricating materials, said that these were used in motor cars for bearings where there was just an occasional movement, such as brake shafts, etc., where the point was too far away to be dealt with by the ordinary lubricating methods, and consisted generally of bushes of porous brass, the porosity being filled with graphite so that the graphite formed a film on the shaft and on the bearing and no lubrication was necessary. He had known some little trouble with that kind of bearing. If the motion was very occasional, and there was no particular load to it, sometimes these bushes seemed to increase in thickness and bind the bearing. There must be sufficient motion to keep the graphite down as it swelled; otherwise the bearing got unaccountably tight. If it was very tight it should be made a little easier. This only applied to a very secondary class of bearing, which might otherwise tend to rust or to deteriorate badly by corrosion. As for using synthetic resin materials and water lubrication, he had had no experience at all of that. He was aware that in water turbines, and machinery which had to work really flooded with water, such bearings were used, but personally he had no knowledge of their having been used in ordinary machine tools at all. With reference to tolerances, Mr. Berry had evidently got what the advertisement described as "a good secondhand lathe." It was quite probably a reconstructed lathe—almost rebuilt—and the alignment corrected in the course of rebuilding, which was possible if it was properly done. In buying a secondhand rebuilt machine, the alignment should be inspected, because usually the persons

responsible for the rebuilding could produce the rebuilt effect more quickly if they did not have to bother with restoring the alignment. (Laughter).

MR. FIELD suggested that what Mr. Wright was saying in effect was that a coat of paint did not make a new machine !

MR. G. W. BROWN asked Mr. Wright's help in elucidating a mystery for him—a very troublesome mystery which he had never been able to solve. Many years ago he had in his charge a 42-inch vertical boring mill. The machine was a failure and they came to this conclusion that they had " bought a pup." The trouble in the particular case was that it was belt driven with spur gear, and the impression of the teeth was left on the work. He took out the spur gearing and put in double helical gears, and still the trouble persisted. He also increased the size of the bearings without effect. The machine was then simply put over for first operation work and the problem was left. He would be indebted to Mr. Wright if he could solve it for him. The speaker gave further instances of difficulties with machine tools, and while admitting that it was not very complimentary to the lecturer, he thought it might lead to light being thrown on certain problems. Anti-friction bearings had been mentioned, and in this connection he described a case in which an American machine had been partly dismantled for erecting. It was found that in one of the horizontal spindles, anti-friction metal had been run round the spindle, and probably the spindle had just been eased in position, but when the spindle was taken out it was found that only about half of the surface had received the anti-friction metal.

Another case was one of a multiple drill, this time a German make. This machine was delivered, put down, and the balance of the head was not correct. It was not purely a question of adjusting weights ; they only got it right by adjusting the fulcrum ; one of the worst errors, probably, they had come across. As he had said earlier, he was not going to be complimentary.

In the case of a lathe which they had put down during the war, he was sure that the spindle had never been bedded in the bearings. When the lathe was put down, and the trouble discovered, they simply packed it up again and sent it back.

Looking through Mr. Wright's paper, one could not help but realise the tremendous progress that had been made, and such cases as those just mentioned, were now very seldom met with. On the whole, the machine tool user had every reason to be proud and pleased with what he got. One was reminded of those stalwarts such as Maudsley and Whitworth ; what would they think if they were to go round a modern works at the present day ? It would be a revelation to them ! Many years ago the speaker had been responsible for trying to standardise machine tools, or the equipment of

machine tools in a very large works; cutting tools, arbors, lathe centres, etc.; and it was amazing the amount of difference that was found to exist. They even found different size clamping nuts on tool boxes. Since those days there had been some progress made, though he agreed with the previous speaker that there was still room for further development.

The thought had occurred to him that if one saw a few machine tools of recent purchase, and found a handle on a wheel that had got bent, on screwing the handle out, it would probably be discovered that it had somewhere about a $\frac{3}{4}$-inch thread into the handle; levers could be come across which had been in use only three weeks, distorted or broken off, and it would seem generally that a lot of these details did not receive the attention they should have from the machine tool maker. With a little alteration in design, some of these levers could be strengthened without making them too bulky.

Mr. Wright said that Mr. Brown's reference to a boring mill was interesting. One of the commonest faults of a boring mill was that in operations it left tooth marks. If, however, he took a smooth file to that job and just wiped it over once, this would take them off. The marks therefore were not of any depth at all, but merely a kind of water mark, and were due to variation in cutting speed as the teeth traversed the table round. Regarding the proposition of the 42-inch boring mill, probably the table was mounted on a spindle of moderate diameter, and had no annular bearing under the circumference. In that case, the slightest imperfection in the teeth would alter the drive from the driving pulley or cone which was some distance away, and allow the table to move with slightly varying velocity, and so produce the water mark effect. He had seen the same thing occur on a fairly large boring mill, and in that case they had found that the table was not properly sitting down on its annular bearing, and when they got the bearing properly down on to the annular bearing, which supported the table, in addition to the central spindle, that generally disappeared. He would suggest that might have been the reason in the case described by Mr. Brown.

Mr. Brown had spoken also about a white metal bearing where the white metal had been economised, and in this connection in machine tools, as a rule, bearings were large in relation to the load they had to carry. It was not merely catalogue matter. Generally, the dimensions of the shafts and size of the spindles were set by considerations entirely independent of the bearing capacity, and an ordinary length of bearing constituted really a very favourably proportioned bearing so far as lubrication went. So that in the case which Mr. Brown had mentioned in which only half the surface received the white metal, it was probably quite sufficient and did its job.

Mr. Brown had spoken sympathetically about standardisation, and the great variety of tools and equipment and of clamping nuts on different parts of the machines. Thirty years ago many hexagon nuts were made in the smithy, and it was said that, if they looked very nice, no one bothered to mill them to 10 per cent. less. Things were not so bad as that nowadays.

Mr. Brown had mentioned handles and levers. If the handle on the lever was sufficient for the effort required in doing the job, it was all right, but if the operator had a spanner in his hand, and rather than put the spanner down and pull the lever, he gave the lever a blow with the spanner, then it was very difficult to cater for that kind of thing. In fact, strengthening the external lever might simply cause the incorrect use to find a weak link in a less convenient place. Such shock action was unfair to the machine. Most machine tool makers would be very willing to make those things stronger if necessary, for legitimate purposes.

Mr. C. Edgar Allen said that one of the fundamental features, in his opinion, which had emerged from Mr. Wright's paper had been the question of slide and bed grinding versus scraping. There were still varying opinions about that, and as Mr. Wright's firm had themselves adopted grinding for several years, perhaps he might give some more information about that?

The first time he had come across bed and slide grinding in Chemnitz, he had duly reported it to a well-known technical director in Coventry, who, after hearing what he had to say, replied: "Over my dead body will slides be ground in this works!" Nevertheless, to-day they were grinding them as a regular practice.

Another point was high speed bearings, and again he must refer to Leipzig, where there was this year a high speed lathe and horizontal diamond boring machine which latter was also shown at Olympia. They had reverted in these machines to solid bearings using a paraffin lubricant. Also in connection with high speed boring difficulties were being experienced in consequence of the high speed, questions of harmonic vibration, and so on, all of which went to point that this new era of extra high speed involved special problems. With regard to the question of centralised control, there was a radial drill produced this year by Kolb, of Cologne, in which every motion except that of the spindle drive was hydraulically operated and three or four buttons on the saddle gave control of everything, from the locking of the table to the speed variation. It would seem that one could not go very much further than that in the way of simplification.

Mr. Wright had also mentioned the question of co-operation between builder and user, which reminded the speaker of a placard he had once seen, while passing through Manchester, displayed in

the window of a small eating house. "Buy our steak-and-kidney puddings! If you don't, we shall both starve!" This seemed to him a particularly good example of co-operation.

MR. WRIGHT referred first to slide grinding, and said that they had been slide grinding for about four years. Ground slides which were now examined showed that slide grinding was superior to scraping in heavily loaded slides such as the table for a milling machine. With scraping there was a considerable tendency to scratching of slides, and with slide grinding that did not so readily occur. Before seriously deciding on slide grinding, they had made tests with flat plates under equal conditions of lubrication, planed, scraped, and ground. These were reciprocated thousands of times with a very small amount of oil on them, and the ground surfaces showed very great superiority over either the scraped or planed.

With regard to high speed bearings, as he had mentioned in the diamond boring and Krauser machine, and in other people's machines for a similar purpose, paraffin and all different kinds of lubricating materials had to be used, and special precautions taken in the bearings. What everybody wanted was an oil of a lightish body, whose viscosity would not change with temperature. They were never likely to get it. It seemed to be admitted, but not accepted up to now, that for the very fine finishing of bores, the lubricated bearing was superior to anti-friction roller or ball bearings.

Though he had been reporting his views on the trend of machine tool design, if he did this again in another twenty years (which was not very likely) he would have to deal with the solution which had been found for this problem. Mr. Allen had admitted that high speed in bearings, and in many other things, was setting problems which were still to be solved, perhaps by the utilisation of some process which was still in the hands of the machine tool makers, and the people who provided the apparatus for carrying out this process.

He had seen the radial drill referred to by Mr. Allen, which had hydraulic movements of all kinds. It also had, though Mr. Allen had not referred to it, a red lamp, so that if the operator tried to start something at the wrong time, the lamp lit, and informed him that he had better do something else to put it right. He had referred to co-operation (not just in the same field as Mr. Allen), but he could not repeat too often that co-operation in this line was essential to progress.

MR. CHAKRAVARTY had noticed that in the Keller die-sinking machine, the speed and feed controls were by electro-magnetic devices, and he inquired if any efforts had been made in British machines to use this system, and what were its possibilities.

MR. WRIGHT replied that the Keller die-sinking machine was rather beyond the scope of the discussion, but on the question of electro magnetic control, machine tool makers and users of machine tools were not ready to confess the limitations of electro-magnetic action. The electro-magnet was a good thing for exerting a big force on something that was almost touching it, but if there was any length of movement, the solenoid was very inconvenient to use. If one could use, say, a magnetic clutch, where the pieces that had to be clutched were almost touching each other, it would be quite easy to use electro-magnetic energy to hold them together. In the case of something that had to move 1½-inches, then the solenoid was going to be a tremendously big thing. A lot of patents had been taken out in recent years for using solenoids for engaging feed gears and to engage and disengage movements, but the danger with those was that unless they were made very liberal in proportion, so that they would operate very surely under exceptionally heavy loads, or unexpected circumstances like that, they were very liable to be troublesome. Mr. Youngash would have something to say about that, as he objected to having a lot of electrical gadgets about machine tools. Mr. Wright said that although his firm had gone quite a long way in electrical equipment, they had kept out of electric solenoids which, they feared, seemed more likely to be troublesome than any of the electrical things which they were at present using.

MR. YOUNGASH said he had been struck by the similarity between the modern machine tool and the motor car. He did not know whether the machine tool maker was copying the car, or whether it was the reverse. He would suggest to Mr. Wright that he go a little further in copying the motor car, and introduce the comparatively recent synchro-mesh gears, which would give him a very effective method of making contact, and a positive drive when he got it home. There was also the question of variable speeds, and what could be better here than to suggest the adoption of a certain well-known manufacturer's recent efforts at infinitely variable gear ?

Then the question of push buttons had been touched on, which reminded him that there had been push buttons on motor cars for quite a long time. If the push buttons on machine tools gave no more trouble in general use than the push buttons on motor car starters, then we should eventually be very happy to have them, but he had doubts on this question. During the past week he had examined some machines equipped with a very fine electrical installation and multiple winding on the armatures of the machine in order to get a number of speeds, and on the front of the machine were two very neat little buttons, one red and one black. But on going round to the back of the machine, he found what appeared to him to be a complete seven valve wireless set !

The question of hydraulics had been discussed, and he did not propose to enter into any further discussion on that point, but he was reminded of a particular machine with which he was concerned which, after standing over the week-end, refused to start on the Monday morning. He had debated for a long time whether he ought to take the fire bucket and put it under the machine to warm the oil, when someone who knew better than he did had come along and taken the oil out and put some thinner oil in.

Oil-less bearings had been mentioned, and perhaps the speaker could remind Mr. Wright of something with which he might be perfectly familiar, that was the use of lignumvitæ bushes. There was another aspect of that problem which possibly might be worth considering. In marine work it was the custom to use white metal bearings on the outer end of the propeller shaft, made of what was called " under-water white metal," and these bearings would work without any other lubrication than water. He was reminded by this of an incident in their own works, when a series of lathes were in hand for overhauling. They were comparatively new lathes, by which he meant that they were about ten years old and had been running twenty-four hours a day during that period. (Laughter). That led to a point he would like to recommend to the machine tool maker. It was that the motor car manufacturer made his car to fetch about £5 after it had done 200,000 miles ; the machine tool maker made his machine to last for ever !

It was thought that the machines had not been properly lubricated, and when they were stripped for overhauling it was found that some bearings had evidently been lubricated with a water base cutting compound. There were in perfect condition ; whereas the oiled bearings were burned out. The meeting could decide for itself whether bearings should be lubricated or not !

Mr. Youngash concluded by proposing a vote of thanks to Mr. Wright for his excellent paper, which received the support and applause of the meeting.

Mr. Wright thanked the meeting for the way in which it had received the vote of thanks, and said that it had given him great pleasure to present the paper, and quite an interesting time in the collection of data. He had been obliged to look again at many machines which he had not concerned himself with for some time.

Referring to some of the points raised by Mr. Youngash, and firstly to the point that the modern machine tool owed a good deal of its design to the motor car, he admitted that it certainly did. The next suggestion, that motor cars should have synchro-mesh gears to give quiet engagement and a positive drive, would be quite practicable if machine tools were driven by petrol engines which gave acceleration, and if they could be speeded up until the synchro-mesh decided that it was the right time to engage. So long as machine

tools had a clutch, and a man to slam a lever over, synchro-mesh would not be very successful.

Variable feeds had been mentioned by Mr. Youngash, and some infinitely variable drive, used in the motor car. He would be glad to hear privately what it was. If one had a feed gear which automatically regulated the feed rate to the cut, it would rush in at a place where the cut was small, and throw the job out when the next lump came round. Advantage could probably be taken of the proportions which the motor car people had laboriously developed for the elements of these things, but the machine tool maker would perhaps use them rather differently.

He could not say anything further about swarf disposal. The machine tool maker was " up against it " here to meet the varying ideas of the purchaser, but they really were trying and spending a lot of money and making a lot of attempts to keep the man as dry as they possibly could.

Mr. Youngash had spoken of push buttons. The push button starter on a car acted very directly on the unit of the motor. If one had a car with a starter of 10 h.p., one would require a seven valve set as well to connect the push buttons ! The machine tool maker did not provide those things for fun. If they could save the £40 for such equipment, they might be glad to do it and get the gratitude of the production engineer just as a side advantage.

As he had mentioned in the course of his paper, lubrication was really the kernal of a lot of problems which were hanging over them. Almost any liquid would do for lubrication for suitably designed bearings. It was, perhaps unfortunately, a tradition that we had to use quite a narrow classification of oils for lubrication, but the speaker had known machine tools run for quite a long time very successfully on a mixture of about seven-eighths suds and one-eighth oil. So long as the conditions were favourable, and so long as the bearings were suitable, there was no reason why they should not run very much longer, but that kind of lubrication was no use for ball bearings. The effect of the rollers and balls of these journals running direct, steel on steel, caused a kind of electrolytic action which actually emphasised the corrosion, if conditions permitted corrosion at all, so that machines having ball bearings would still have to be lubricated with something in the oil line.

METALLURGICAL POST-MORTEM EXAMINATIONS.

Paper presented to the Institution, Sheffield Section, by G. E. Howarth, A.Met.

Introduction.

NO doubt most of the members of the audience will be familiar with research department or laboratory reports, and in some cases may possibly, with some reluctance, have had to accept the decisions therein. It is my object to-night, therefore, to show you as well as my limitations will permit, how such decisions are arrived at, and to indicate the close similarity between a medical post-mortem examination, and the examination of any steel part which is found to be defective during course of manufacture, or has failed in service.

As pointed out by the late Professor Osmond, one of the pioneers of metallography, the study of metals is very analogous to medical science, and can be classified quite logically into three main divisions : *anatomical, biological, and pathological.*

The first division, *anatomical*, includes the study of the structures of metals and alloys, and their physical properties. The second division, *biological*, can be taken to include the variations in structure and physical properties caused by both hot and cold work, and by heat treatment. The third division, *pathological*, obviously refers to the study of the effects of ill-treatment, either congenital or during subsequent fabrication, and the influence of impurities. In other words the diseases of metals.

The subject of this paper, post-mortem examinations, therefore comes within the scope of the last classification, but a thorough knowledge of the other two divisions, of course, is necessary in order to carry out an accurate diagnosis. One important class of post-mortem work, however, which should logically be included in the second category, is the examination of what the biologist would classify as "sports." Parts which have given unusually good performances are dissected in order to arrive at the cause of their abnormal physical development, so that the race in general may be brought up to their level. As far as time permits, I shall endeavour to explain to you some of the diseases which steel is subject to, their causes and effects, and some few post-mortem investigations of special interest.

Preliminary Inspection.

As complete a history as possible of the " body " in a metallurgical post-mortem examination is quite as important as in a medical inquiry, and this point requires emphasising, as some examinations are rendered more difficult and inconclusive because of the lack of sufficient data. Similarly to its medical counterpart, the necessity that the " body " should not be mutilated in any way after death is of considerable consequence, because any subsequent damage may destroy symptoms of the disease which may have led up to the failure. For instance, where failure has occurred by fracture, the appearance of the fracture gives indications which are not only a clue to the causes determining failure, but also will indicate on what lines the post-mortem examination should proceed. In general, most failures by fracture may be classified under three headings :

(*a*) Sudden fracture without appreciable distortion, under shock or steady stress. Metals which are unduly brittle are liable to fail in this manner, so that one of the obvious things it would be necessary to determine in a failure of this kind would be the ductility and toughness of the material.

(*b*) Those cases where fracture has occurred by direct overstressing in tension, shear or torsion. In such cases it is necessary to ascertain whether the material is of satisfactory strength, as if so, it may be quite logically concluded that the stresses applied have been greater than permissible.

(*c*) The third class includes failure by " fatigue," and possibly is the most important of the three, as the fracture of most moving parts, such as crankshafts, axles, connecting rods, etc., is usually due to this cause.

I wish to deal more fully with this most important and interesting type of failure at a later stage, after having described some of the most frequent types of defects.

Each type of fracture has its characteristic appearance, and in general is readily recognised. Frequently the examination of a fracture will show indications of its starting point, so that attention can be focused on such a position in order to ascertain whether any initial defect is present. The preliminary visual examination is, therefore, perhaps the most important step in a post-mortem examination, as it is necessary to clearly make up our minds what points require elucidation and to concentrate on such essentials. As in a medical inquiry having diagnosed the general complaint, attention may be directed to the seat of the trouble. A preliminary survey having been made, the examination proceeds in the direction indicated, but briefly the general methods employed are as follows :

Chemical Analysis.

Chemical analysis is necessary not only to determine that material of satisfactory purity has been employed, but also to ascertain that a suitable quality of steel has been used for a specific purpose. A customer may on his own initiative, order a certain steel for a purpose to which it is quite unsuitable. A complaint arising from this cause is easily dealt with. On the other hand, with the large number of steels now in demand, very great care has to be exercised to ensure that all the different qualities are kept separate. Due to the methods of checking now available, such as spark testing and spectroscopic analysis, confirming where necessary by chemical analysis, cases of mixing should not occur, but it will be readily understood that when these methods were not available occasional instances led to disastrous results, the author having encountered cases where an intensive hardening steel had been supplied in error for a case-hardening quality.

Physical Properties.

When actual fracture has occurred in service some doubt may be entertained as to the physical properties of the material. If the sample permits, tensile, bend, and notched impact tests are removed as close as possible to the fracture in order to ascertain that suitable strength, ductility, and toughness are present. Toughness can be defined as the resistance to the propagation of a crack, and is measured by the energy absorbed in breaking a notched test piece, usually by a single blow. Brinell tests at numerous positions are also made to determine that the physical properties are uniform. If any deficiences are disclosed, the next step is to ascertain from what cause these have arisen, whether they are due to defects in the material itself or to ineffective heat treatment, and the appearance of the fractured test pieces are of some significance in this connection.

Macro-examination.

The term " macro-examination " refers to the examination of large scale structures, visible to the naked eye or with the help of a hand lens. In carrying out investigations into the causes of failure of steel parts, a knowledge of the macro-structure is just as essential as the micro-structure. The former, when correctly interpreted, gives the history of the steel in the ingot mould and during forging, and the latter information as to the heat treatment and the composition. Time is not available to describe at all adequately this very interesting method of metallographic examination, except to point out that by its means the congenital diseases of steel, that is those produced during melting and casting, are disclosed. The most common of such defects are :

(*a*) Blowholes, which may give rise to surface defects, such as rokes and seams, during subsequent forging, rolling, and stamping, and in some instances are the cause of hardening cracks during heat treatment.

(*b*) Slag inclusions. Under this general heading all the non-metallic inclusions present in steel are frequently included, although they may be the result of very diverse causes. If the size or amount of such inclusions are excessive, their presence may be shown by visible specks on the machined surface or from the occurrence of defective test pieces, as from a strength point of view, they are more or less equivalent to voids or cavities, and may give rise to low ductility figures.

(*c*) Annular or secondary segregation at positions well below the surface of the ingot or forging, which unfortunately is sometimes exposed during machining and gives rise to ghost lines.

(*d*) Axial segregation and axial unsoundness or " piping."

(*e*) Ingot corner weakness is a more uncommon type of defect, although the liability for its development increases with the ingot size. Sometimes when present in large forgings, it is only discovered during final machining, and is easily recognised as thin attenuated threads of segregate, sometimes accompanied by fine cracks. In extreme cases such weakness may develop during hot working into actual bursts. In the case of pressure vessels, or at the toothed periphery of rapidly revolving rotor shafts, the occurrence of pronounced defects of this type might have serious consequences, and all such forgings should be carefully examined to ensure their absence.

(*Each type of defect was illustrated by means of suitable lantern slides.*)

Other ailments which are liable to be contracted during fabrication may be detected by this method of examination, a very common one being that of " lapping." Laps, of course, are due to the folding over and crushing inwards of fins of metal during forging and rolling, the oxidised skin or scale being pushed into the material, giving rise to a seam. The difference between seams produced by this mechanical operation and those due to the condition of the original ingot skin may be distinguished by suitable methods of etching. In the first case, the " flow of the grain " round the defect clearly indicates its origin, and in the latter case the presence of associated blowhole segregation is a means of distinguishing the two types of defect. It will be realised that the correct diagnosis of such defects is of some importance, otherwise the steelmaker may be blamed for a remission on the part of the forge or rolling mills.

(***Lantern slides showing the difference between these two types of defect were thrown on the screen.***)

The "Grain of Steel."

A word should be interposed at this stage with regard to the "grain of steel." The "grain of steel" is due to the persistence of the "cored" or dendritic structure present in the ingot. This structure persists right throughout subsequent operations, being merely distorted, and where considerable longitudinal extension has occurred, as in a rolled bar, the original dendritic structure is drawn out into fibres. It will be realised, therefore, that the physical properties with and across the "grain" may show differences, a close analogy being that of wood, which is easier to split with the grain than across it. This is one of the reasons why in the case of drop forgings such care is paid to ensure that the "grain" shall closely follow the contour of the surface, so that the major stresses shall always be normal to the "grain," and why a drop-forged crankshaft is stronger than one machined from a billet.

(*A lantern slide of a drop forging with an unsuitably disposed "grain" was shown to illustrate this point.*)

Forging and Heat Treatment.

Another feature which can be determined by macro-examination, is the efficiency or uniformity of the structure produced by forging and heat treatment. For instance, if a bar were heated at one end to a hardening temperature while the other end was kept cold, and then the whole quenched, a sharp line of demarcation would be shown by etching between the hardened and unhardened portions. The effects on the structure produced by local heating such as is obtained by welding, flame cutting, or other causes can be disclosed. If two or more materials of differing composition have been welded together, the variations shown by the etched surface indicate their presence and accurately disclose their limits. This method is of considerable importance and has been the means of demonstrating in a very clear manner, faults which would not have been so readily admitted. This method of etching also reveals the presence of any actual discontinuities in the metal, such as very fine cracks.

(***As an illustration of the information to be obtained by this method of etching, a section through a drilling bit was shown, which had been made of iron and steel, and locally hardened at the cutting edge.***)

Micro-examination.

For all practical purposes steel may be considered to consist of two components, soft iron or ferrite and a hard constituent, carbide of iron. The physical condition of a steel depends on the mixture of these two components.

In the cast condition the particular crystallographic form of the ferrite and the carbide of iron which can conveniently, although not

accurately, be referred to as pearlite, in its well defined coarse lattice or Widmanstatten arrangement, has physical properties of a relatively low order, the ductility and toughness being particularly affected. Forging breaks down this undesirable structure and produces a much finer grain, but if the forging or rolling operation is finished at too high a temperature the " as cast " structure is more or less reproduced. By reheating to a red heat, the iron and carbide of iron mutually dissolve to form a solid solution, which, if slowly cooled as in an annealing treatment, besides refining the structure due to the recrystallisation which occurs, also produces a very complete separation of the two constituents, so that the influence of the soft ferrite is very pronounced and consequently the strength is relatively low, although the ductility is high. If, on the other hand, the solution formed at the high temperature is quickly cooled by rapid quenching as in the hardening operation, only a partial breakdown of the solid solution, austenite, takes place, giving rise to a hard constituent known as martensite which, although having great strength, is relatively brittle. Tempering, however, breaks down this constituent into ferrite and carbide of iron in an ultra-microscopic state of division in which condition the best all round physical properties are obtained, that is relatively high strength with good ductility and toughness. This condition therefore, is the one which is desired in structural steels. If, however, the tempering treatment is carried too far the carbide particles coalesce into nodules, and the structure consists of carbide spheroids in a ferrite matrix. For ease in machining, this structure is intentionally produced with certain tool and alloy steels before final treatment, as in this condition the steel is at its maximum softness, but as it has a particularly low yield point and is deficient in toughness, such a condition is avoided in highly stressed parts. It will be seen, therefore, that the physical condition of a steel depends on the degree of separation of the two constituents and the state of division of the carbide component. These can be recognised by micro-examination, and the heat treatment employed can be determined.

(*Photomicrographs of a* 0.30 *per cent. carbon steel in various stages from the ingot to the final heat treated condition, and showing the influence of structure on the physical properties were thrown on the screen.*)

" Burning."

There is one dangerous condition in steel which perhaps should be referred to and that is " burning." The " burning " of steel or any other alloy occurs when it is reheated into a range of temperature where it is partially liquid. In this range the portions of the steel which were last to freeze during solidification are the first to melt and they segregate to the grain boundaries. As these portions

contain the impurities, a very dangerous condition is arrived at. Further, the gases present in solution in the steel are driven off at the high temperature and tend to produce actual microscopic voids at the grain boundaries. Air readily penetrates between the grains and films of oxide can be recognised under the microscope. It will be realised, therefore, that in this range of temperature there is little cohesion between the crystals and the steel is in such an exceedingly fragile condition that if hammered, rupture easily takes place. When this occurs, the surface of the fracture or burst shows a granular appearance like coarse sugar. The careful control of the reheating temperature in forging and rolling operations, therefore, is necessary because steel which has been " burnt " is unsafe to use, and nothing short of remelting can put it right.

(*Slides showing the effect of " burning " on the micro-structure were thrown on the screen.*)

Fatigue Fractures.

Having considered briefly some of the diseases which steel is prone to develop during its birth and subsequent growth or fabrication, the final stage in the sequence would appear to be some account of the ailments which are experienced in maturity, in this case service. In this connection, we will consider chiefly one type of failure, and that is failure by fatigue, as by far the greater number of failures of moving parts are due to this cause.

If a crankshaft, axle, connecting rod, or other moving part, which is subjected to stress either of a rotary or reversed type, breaks suddenly, and shows a smooth type of fracture with conchoidal markings something like the annular rings on the cross section of the trunk of a tree, it may be concluded that failure has resulted from fatigue.

The process of fatigue has been studied under the microscope, and it has been shown that when steel or any other ductile metal is subjected to repeated stresses above a certain value, plastic movement takes place by means of exceedingly slight displacements within the crystals themselves. This movement is known as " slip " and occurs along certain crystallographic planes, in a manner somewhat similar to that which takes place when a block of toy bricks is slightly displaced. Movement by " slip " causes a redistribution of the stress, but further applications of stress develops more and more slip lines, until eventually a stage is reached when actual rupture occurs, and a microscopic crack makes its appearance. When this has occurred then ultimate failure is certain as the resulting stress concentration at the base of the tiny crack ensures its further development, and the growing " fatigue flaw " progresses through the metal until such a time as it can no longer sustain the dead load and final breakdown occurs suddenly. It will be gathered that a

fatigue flaw is transcrystalline and progresses in detail from crystal to crystal. Due to rubbing between the opposing sides of the growing flaw the characteristic smooth appearance is obtained.

The " fatigue " of metals, therefore, takes place when the material has been subjected to repeated stresses which have exceeded a definite value known as the " fatigue limit." If a moving part is subjected to stresses below this value its life will be infinite, but if for some cause or other the " fatigue limit " is exceeded, then failure ultimately occurs. The " fatigue limit " which, however, can be accurately determined by somewhat lengthy tests is not definitely related to any other physical property, the tensile strength with ferrous materials being the only property to show any relationship, although obviously when stressed within the fatigue limit, metals must behave in an elastic manner. It can be stated, however, that steels which have been heat treated so as to obtain a fine crystalline structure with uniformly fine dispersion of the carbide are in a condition to withstand alternating stresses of a higher order than materials of coarser and more heterogeneous character.

It will be realised, therefore, that fatigue failures are due to overstressing. Such overstressing can and does arise from the application of excessive loads, either from failure to realise the limitations of a material or from miscalculations in the stresses imposed. On the other hand, a more common cause for the development of fatigue flaws is local concentration of stress, caused by sharp changes in section, such as inadequate radii, sharply cut fillets, unduly pronounced tool marks, severe local cold working, misalignment, or even imperfections in the steel itself. Internal defects may result in fatigue failures, and cases where the presence of an internal " pipe," forging rupture or "clink " resulting in the outward growth of a fatigue flaw and consequent failure have been experienced.

It should be pointed out that where a moving part is adequately supported by bearings, such as an aero crankshaft, as high a fatigue strength as possible commensurate with a reasonable amount of toughness is desirable and steels of high tensile strength are, therefore, used for this purpose. In the case, however, of parts such as locomotive crankaxles and tramway axles on certain systems which are subjected to occasional severe overloads due to track conditions such as faulty crossings, unduly sharp curves and other causes, softer material is found to be superior in spite of its lower fatigue strength. This is due to the fact that the softer material can locally plastically deform without rupture to a greater extent than harder materials, and so redistribute the stress so as to avoid crack formation. This would appear to be due to the distribution of the ferrite and carbides. In the harder materials, the two constituents are in an intimate state of division, and the carbide particles act as keys

which hinder slip, whereas with a structure containing free ferrite, slip can occur more readily.

(*Typical fatigue fractures were shown, and cases described and illustrated where fatigue failures had occurred as a result of local stress concentration arising from various causes. One instance where the initial fatigue flaw had commenced as a result of the intercrystalline penetration of a fluid foreign metal during course of manufacture was described, and a short resume of the causes giving rise to a metallic interpenetration was given, indicating that the surface of steel and other metals when subjected to tensile stress in the presence of a fluid foreign metal may be cracked and disintegrated by an attack along the crystal boundaries.*)

Corrosion Fatigue.

The fatigue limit of steel when subjected to the influences of corrosion is lowered to an alarming degree, some tests by Dr. Inglis showing that a mild steel having a fatigue limit of $\pm$ 17.0 tons per square inch, when in contact with River Tees Water, gave figures of less than $\pm$ two tons per square inch. It has been shown by Ulick Evans that all metals are protected by a thin film of their oxides. This film is only a few molecules thick, and under the influence of repeated stresses, is rapidly broken, which sets up electrolytic corrosion, and leads to the formation of surface pits or fissures. When once pitting has started, then fatigue sets in due to stress concentration at the base of the pits, but is undoubtedly accelerated by the corroding influences.

(*A tramway axle which had broken within the wheel seat as a result of corrosion fatigue was described as an example of this type of failure.*)

Miscellaneous Failures.

I propose to refer only to one example under this heading, and that is another example of interpenetration, in this case a railway straight axle. The axle developed a hot box, and when taken out for examination the journal dropped off.

The scored surface of the journal and the unusual discoloured granular appearance of the fracture was clear. On sectioning the journal and the adjoining wheel seat, it was shown by etching that due to the frictional heat generated by "seizing" in the bearing, the whole of the journal had been raised to a red heat, the transition line between the altered and unaltered original structures being shown by a slide. Micro-sections from the surface showed a film of brass surrounding the crystalline grains, and it was evident that the surrounding bearing metal had been fluid. The failure was due, therefore, to the twisting off of the journal when it was raised to a full red heat and greatly weakened by the interpenetration of the molten

brass, which accounted for the unusual characteristics of the fracture.

With this interesting failure, I will close.

Discussion.

MR. LAMBERT : I would like to ask if in the case of penetration of bronze into steel would the bronze be entirely segregated in the structure ? In the latter case would not the metal be much weaker than the original steel ? I should also like to know whether penetration takes place with all steels.

MR. HOWARTH : It is only when the bronze is fluid and the surface of the steel under tension that interpenetration occurs. Under these conditions the fluid bronze attacks the steel along the crystal boundaries and penetrates inwards from the surface as microscopic threads or canals. The bronze, therefore, is most sharply segregated. The steel while the bronze is fluid has only the strength of the fluid cement which is nil, so that rupture occurs. When, however, the cement has solidified the strength of the complex would depend on the respective strength of the crystals of steel and of the cement. As regards ease of penetration it has been shown that metals having the most simple crystalline structures are the most easily penetrated, so that although I cannot speak from actual experience, while penetration possibly may occur with all steels, the ease or extent of the penetration would not be similar.

MR. LAMBERT : I was under the impression, in the case referred to, that the axle housing was hot.

MR. HOWARTH : Yes, the frictional heat in the bearing had been so great that the journal had been heated above the recalescence points of the steel.

MR. LAMBERT : Had not the fluid bronze on the steel a similar action to mercury on certain bronzes ?

MR. HOWARTH : Yes, the action is similar.

MR. JOHNSON : Is there any method of normalising steel when it has been heated above the average temperature ? Would it be possible to bring it back to its cast state ?

MR. HOWARTH : Overheating reproduces to some extent the cast structure, which, of course, is an undesirable one. Normalising by reheating to a temperature above the change point produces recrystallisation and refines such an undesirable structure. If, however, the steel has been heated to very excessive temperatures and actually " burnt," that is partially molten, then no form of heat treatment will restore it.

MR. JOHNSON : Does that apply to all steels ? Assume you have a piece of tool steel in the furnace and you left the muffle door open, so that the temperature rose far beyond the critical point, two or three hundred degrees, until you got it almost molten when the steel was turned out, would you then be able to machine the surface off it,

and bring the core, which was not in the same state as the exterior, back to the normal state ?

MR. HOWARTH : Yes, all steels so far as I know can be " burnt." To " burn " a steel the temperature required would, however, need to be higher than two or three hundred degrees above the change point. Whether the core could be restored would depend on the extent or depth of the burning. If this had not penetrated deeply the core could be restored. Assuming the steel could be fractured, the appearance of the fracture would enable one to ascertain the depth of the burning. Different qualities of steel, however, which have been seriously overheated are not equally easy to restore.

MR. BALL : I am interested in the welding of steels by the electric arc process, and should like your opinion as to whether F.S.T. steel would be spoilt by welding to mild steel. It struck me that some interpenetration effect might occur during the welding operation which would spoil the stainless steel, and I should like to know whether the stainless steel is affected at the weld by the mild steel. Take for instance a stainless steel pressure vessel. On the outside a steam jacket is welded. There are cases where the stainless steel is affected by the welding on of the mild steel. It is probably just due to the contact of the two metals. With regard to copper bearing steels it has been proved that these steels which are supposed to be weather resisting have failed. It struck me that some form of interpenetration might be the cause of this.

MR. HOWARTH : Stainless steel quite definitely can be welded satisfactorily to mild steel. In the qualities mentioned by you any local corrosion due to " weld decay " should be absent. The weld metal, of course, is virtually in the cast condition and, therefore, has not the same resistance to corrosion as the adjoining unaffected metal, although I should not like to say that the corrosion resistance properties are seriously diminished. The welding operation is a fusion process, both steels being molten along the joining, and so far as I am aware no intercrystalline penetration of the mild steel into the stainless steel occurs, or vice versa, but of course at the junction some diffusion must occur. I can understand corrosion occurring in the mild steel adjacent to the weld, due to electrolytic attack, the mild steel being anodic.

In the case of the copper weather resisting steels you mentioned, containing about 0.25 to 0.5 per cent. copper, the copper is entirely in solid solution in the steel, and no segregation of copper at the crystal boundaries is present. Although I have no experience I understand that with these steels while corrosion occurs in the early stages at a similar rate to ordinary mild steel, later the rate diminishes very considerably, due it is thought to the formation of a film of high copper content at the surface. General experience appears to indicate that the corrosion resistance is undoubtedly

increased by the addition of copper, although the beneficial effect depends largely on the conditions of service, and when the steel is in contact with water no benefit is derived from the presence of the copper. If chlorides are present in the water I believe it has been found that corrosion occurs at a greater rate than with mild steel. Of course, copper bearing steels have nothing like the same resistance to corrosion as the different highly alloyed stainless varieties.

MR. WILLIAMS : I think the trouble which Mr. Ball speaks about is an electrolytic trouble more than anything else. If you weld stainless steel to mild steel you get a very high electric potential difference between the two metals at the juncture, and corrosion will always start in cases like that. We have had similar cases which we have put down to this difference in electrolytic action. I was interested in Mr. Howarth's remarks about the fatigue limit, and taking as a criterion the ultimate tensile strength. For a long time I have always regarded the yield point as being the best criterion of the fatigue limit of steel, and I think that many people would be very interested to hear that the tensile strength is probably the best guide to judge steel. I shall be interested to hear Mr. Howarth's views regarding the yield point.

MR. HOWARTH : No, I do not think the yield point can be taken as the best guide. The determination of the elastic limit and the yield point depend to a very large extent on the accuracy of the measuring instruments, and although mild steels show a well defined yield point, in alloy steels of the air-hardening variety, especially in the hardened condition, the point is indefinite and apparently low. Such material, however, has a high fatigue limit. It has been shown quite definitely by Dr. Gough of the National Physical Laboratory, that the fatigue limit, from results obtained from a large number of steels, bears no uniform relationship to the elastic limit or the yield point, but on the other hand using a similar wide range of materials the fatigue limit was found to be approximately 0.46 of the maximum stress, and that working on this figure the error is not likely to be greater than $\pm$ 10 per cent.

Further, Bauschinger showed as early as about 1880, that the elastic limit as determined by a tensile test was very different from that obtained after the material had been subjected to cyclic stresses. The first mentioned point he designated the primitive elastic limit, and this can be considerably lowered or increased by repeated stresses. I would refer Mr. Williams to Dr. Gough's book on the " Fatigue of Metals," where all the points raised will be found to be dealt with in detail.

MR. FIDLER : I take it that the yield point is of value if the article is only subjected to a static load, and not a dynamic stress. The conditions are not the same as they would be in a crankshaft. Can

you take the yield point as some guide as to the quality of the steel required ?

MR. HOWARTH : Yes, the yield point or proof stress is, of course, of value in parts subjected to a steady static stress or dead load, and such a determination indicates at what load permanent stretch or deformation will occur. In the case of a crankshaft where no permanent deformation or alteration in shape is permissible the yield point is of no special value, the fatigue limit being the vital consideration. It has been shown that very similar phenomena occur in materials when subjected to cyclic stresses as that which occurs during the magnetisation of iron or steel. At safe stresses within the fatigue range early applications of stress shown on a stress strain diagram a distinct loop, the extension not being in proportion to the applied stresses. No doubt during the period the material is settling down and local plastic deformations are occurring so as to even out the applied stresses. A second stage is reached with further stress applications, and the material becomes elastic, that is the stress and strain are proportionate and the curve becomes a straight line. This elastic range is the safe range and the material in this condition will withstand an indefinite number of applications of stress. At greater stresses outside the safe range an elastic condition is not obtained and continuous plastic flow occurs until ultimate breakdown results. The elastic range obtained by repeated stresses bears no relationship to the limit of proportionality or the yield point as shown by the tensile test. The yield point, however, is not without value, and certainly indicates the efficiency or otherwise of heat treatment.

MR. CLAXTON : From the lecturer's remarks one might assume that most of the problems relating to steel can be solved by a post-mortem examination. What would happen when all the recognised methods of procedure are exhausted ?

MR. HOWARTH : I should not care to guarantee that every problem in connection with the behaviour of steel can be solved by post-mortem methods. Besides dissecting bodies constructive work is sometimes necessary to get to the bottom of a trouble.

MR. CLAXTON : I had an experience of this kind. A certain steel containing one per cent. tungsten and one per cent. carbon cracked during the hardening process, and the trouble could not be solved. It all happened in the tempering process and we were not able to discover where. We changed the steel at the finish and the trouble disappeared.

MR. HOWARTH : It would appear that by quenching samples from differing temperatures and noting the results after tempering, the trouble might have been overcome. Without having an opportunity of investigating the problem I would not care to express any considered opinion.

MR. WILLIAMS : I would like to return to this question of fatigue, and ask if ductility enters into it at all. I refer to ductility represented by the percentage elongation.

MR. HOWARTH : In the case of loco crank axles, I think Sir Henry Fowler has shown that ductility does enter into it. He found that as the carbon decreased, and the elongation per cent. increased as shown by tensile tests, the life increased, but this is a special case of fatigue and not a general case.

MR. WILLIAMS : I was wondering if there is any relationship between fatigue limit and elongation.

MR. HOWARTH : I do not think there is although Gough states that : " Generally speaking it may be said that low and medium carbon steels, in the normalised condition and possessing great ductility, usually reveal comparatively high ratios of fatigue limit to tensile strength but the author wishes to emphasise that it is useless, at present, to attempt to convert this generalisation into a definite rule." On the other hand it is now well recognised that parts which are known will ultimately fail by fatigue, and which are subjected to occasional and possibly periodic overloads much higher than the fatigue limit, will give a longer life if made in relatively soft steel with high elongation or ductility values than in steel with a higher fatigue limit but diminished ductility. Examples of this are locomotive crank axles and tramway axles where stresses of unknown magnitude are superimposed on the mean stress due to track conditions and other causes. Under such conditions the ductility comes into play by the ability of such material to locally yield so as to redistribute the stress, and so avoid the development of a crack. The speed at which a crack will progress is also diminished.

A VISITOR : In the case of a tramway or railway axle, does not another component come in ? In the case of a railway axle you get very great impact stresses owing to trains running over points.

MR. HOWARTH : Yes, suddenly applied shock overloads, which can be withstood to a greater degree by a material having considerable ductility and toughness rather than a high fatigue limit.

A VISITOR : In which case a harder steel would fracture quicker than a mild steel.

MR. HOWARTH : Yes, that is general experience. In the case, however, of say an aero crankshaft which is adequately supported and not subjected to suddenly applied overloads, steel with a high fatigue limit is required and under such conditions a mild steel would last only a very short time.

MR. WILLIAMS : I believe Continental opinion rather favours the impact test as a very good indication as to what the fatigue results of a metal will be, and I should like to have Mr. Howarth's opinion on this point.

MR. HOWARTH : Results have shown that there is a total lack of relationship between single blow impact tests and the fatigue limit. In the special case, however, where the stresses applied are entirely shock stresses, such as in gear wheel teeth, Rowe has shown that a high impact value is of importance in resisting this special form of fatigue. Since toughness is defined as the resistance to the propagation of a crack, it is conceivable that a fatigue flaw once started might take longer to travel across a tough material than a brittle one. I do not know, however, whether any work has been done in this connection. Experience appears to indicate that a fatigue flaw progresses to greater extent before final fracture occurs in a tough ductile material than in a brittle one. Certainly toughness and ductility are of value in materials which are required to withstand suddenly applied overloads since with such properties local deformation is more likely to occur so as to prevent the formation and spreading of a crack.

MR. FISHER : Could I ask a question with regard to normalising ordinary mild steel of 26/30 tensile strength ? The Board of Trade Regulations suggest that the steel should be normalised, especially welded steel, but they do not give a temperature. If you could give me a figure I should be much obliged. With regard to the burning of steel, I have never seen any definition of burnt steel. How can you tell which is burnt steel and which is not ?

MR. HOWARTH : A normalising treatment as defined by the British Standards Institution Committee consists of heating the steel to a temperature of not more than 50 degrees C. above the upper limit of the critical range and then allowing it to cool freely in air. The temperature, therefore, depends on the carbon content of the steel, and mild steel should be reheated to about 900 degrees C. while with about three per cent. carbon 850 degrees C. would be high enough. In your case, assuming about 0.2 to 0.3 per cent. carbon between 850 degrees and 900 degrees C. should be alright.

With regard to burning, as pointed out in the paper this only occurs when steel is heated above the solidus line, that is to a temperature where it is partially liquid. This temperature varies with different steels and figures published by Jomeny in America show that burning does not occur below 1,450 degrees C. with a mild steel, but with a 90 carbon steel 1,300 degrees C. should not be exceeded. These values, however, do not hold if the furnace atmosphere is oxidising and turbulent, and, therefore, in practice " burning " would occur at distinctly lower temperatures. The best test for " burning " is the appearance of the fracture. A granular appearance in which the grains stand out like crystals of sugar as distinct from the more usual flat crystalline appearance is conclusive evidence of " burning." The appearance of the surface scale is also a guide.

MR. WAITE : There was one slide which interested me very much. That was the corner cracking of ingots. Is that a very common affair ? How does it happen ?

MR. HOWARTH : It is not a common occurrence, although the danger of corner cracking increases with the ingot size. There are two theories for this occurrence. Of course you realise that when steel is poured into an ingot mould, solidification commences from the mould surface and progresses inwards. The crystals first formed grow inwards with their axes at right angles to the mould surface, so that at the corners of the mould there is a sharp line of demarcation between two sets of crystals growing in different directions. At such a position there is a tendency for impurity to be trapped, small contraction cavities and cracks to form, as well as weakness due to the sudden change in orientation of the crystals growing from the opposing sides. This theory is held by some metallurgists to be the cause of the trouble. Another theory, however, is that fluid pressure from the molten interior plays a part in the trouble, and that an actual rupture running from the inside towards the surface is produced at the weakest portion of the solidified skin, which for the reasons already mentioned is the corner. This crack is subsequently filled with segregate, such as was shown by the slide. This latter theory appears to meet the observed facts most closely, as it is found that frequently the corner cracks or segregate do not reach the surface, that they usually are confined to the bottom portions of the ingot where the fluid pressure would be greatest and that cracks of a similar nature can be produced in round ingots. To avoid the trouble the metal should not be cast too hot or poured too quickly.

MR. FIDLER : I would like to ask Mr. Howarth for an explanation as to the cause of cracking of case-hardened articles other than that caused by improper grinding, and how he can distinguish cracks caused through improper grinding from those resulting from improper carburising.

MR. HOWARTH : Mr. Fidler has himself answered the first portion of his question. Cracks arising from the two causes can be distinguished by etching. The structure will show a streaky appearance if the grinding operation has been at fault. If improper carbonising has occurred, giving an unduly high carbon concentration in the outer layers microexamination will show the presence of excessive amounts of carbide. The shelling or flaking of the case can often be traced to the presence of a network of excess carbide.

MR. WILLIAMS : It gives me very great pleasure on your behalf to thank Mr. Howarth for his very excellent lecture. The first part of the paper, I think, brings home to all of us the necessity of having the materials we use in their proper conditions, and I think that this is something which is going to become of greater importance in the future than in the past. No less interesting was the section dealing

with fatigue results, because these are known within the experience of the majority of us. I must say that his replies to the various questions have been very interesting. I think that in themselves, they have almost constituted a lecture.

MR. COOPER seconded the proposition, which was carried with acclamation.

PROCEDURE CONTROL OF ELECTRIC WELDING.

Paper presented to the Institution, Yorkshire Section, by J. E. Kennard.

SO wide and diversified is the field covered by electric arc welding in its present stage of development that the problems which confront production engineers, engaged in various phases of industry, may be widely different. Welding in structural engineering, for instance, consists very largely of making small fillets in situ between members of relatively small cross section; the mechanical engineer, on the other hand, may be engaged in butt welding circumferential and longitudinal seams of a pressure vessel several inches thick. Similarly other branches have their own special requirements, so it is obvious that any system of procedure control is only suitable for the particular class of work for which it is devised.

No attempt is made in this paper to indicate the author's views as to how any piece of welded construction should be proceeded with; that is a matter for the individual engineer who is better fitted by training and experience in his own sphere to evolve systems conducive to economical production. There are, however, certain fundamental principles common to all welded connections which vitally affect their efficiency and influence the financial aspect, and it may be of interest to review some of these aspects.

Weld Efficiency.

The essential difference between the riveted and welded methods is that the former is a cold semi-rigid form of construction which depends upon accessories to provide the strength to withstand loading stresses, whereas welding is a thermal process solely dependent upon the degree of homogeneity of the junction, thus formed, for its efficiency. This being the case a brief review of the factors which affect efficiency may not be out of place, neglecting for the moment the skill of the welder. The metallurgical changes identified with welding of course play the most important part, but recent investigations indicate that the contour of the joint has a material influence, to which reference will be made later. Neglecting for a moment any subsequent heat treatment that may be applied, it may be said that the structure of weld metal is of two different kinds—coarse and

Leeds, January 30th, 1934.

refined—depending on the method of making the weld. In a weld made in one operation, i.e., with one pass of the electrode, the molten metal is rapidly cooled from a superheated temperature by the heat capacity of the plate and a structure identified with primary crystallisation results, with the notable difference that owing to the rapidity of cooling the grains are much smaller than those found in any ordinary sand casting and the " pearlite " is distributed in fine particles throughout the " ferrite." The plate area immediately adjacent to the fusion zone is heated to a temperature not far below the melting temperature. In short the plate at that particular spot is overheated, and this condition, assisted by the contraction of the cooling weld metal, induces grain growth in that part of the plate. A little farther away from the weld the temperature to which the plate has been raised corresponds roughly to the nomalising temperature for mild steel which, in association with rapid cooling, produces a fine structure identified with " Sorbitic Pearlite." As we move away from the weld the heat induced into the plate from the welding operation decreases, with a corresponding decrease in diffusion of pearlite until a point is arrived at where the plate shows no structural change. It will be seen, then, that single run welds suffer from two features which render them inferior to the basis material—the relatively coarse structure of the weld metal and enlarged grains in the parent metal adjacent to it—both of which adversely affect the physical properties of the joint, particularly its impact and alternating stress values.

Multiple run welds exhibit a marked superiority over the single run type by reason of the automatic heat treatment applied to the underneath layers by the subsequent runs. Each superimposing run refines, by normalising, the one underneath and reduces the area of grain growth to the same fine structure. By suitable manipulation a uniform small grain equi-axed structure can be obtained throughout the weld area.

The following figures are typical of the relative efficiencies of single and multiple run welds produced with high class modern electrodes under good operating conditions.

	Tensile Tons per sq. in.	Elongation on 2-in. per cent.	Bend on 2T degrees	Izod ft. lbs.
M.S. Plate	29.1	40	180	48
Multiple Run ...	29.2	24	180	60
Single Run	29	14	110	24

The importance of weld efficiency in respect to the individual physical properties becomes apparent when considered in relation to the nature of the loading stresses of different kinds of structures. In statically loaded structures such as pressure vessels, building constructions, bedplates, etc., yield point and ultimate strength are

the factors which govern their strength and determine the sizes of the section employed, while ductility is an essential property for the alleviation of dangerous stress concentration due to various causes. Other kinds of structures which under working conditions are subjected to vibratory, impact or shock stresses of various types, such as railway rolling stock, bridges, transmission shafts, etc., call for the additional properties of high resistance to such stresses. A notable example of the latter is a welded diesel engine frame in which under working conditions high combustion pressures combine with the inertia loads of the moving parts to throw heavy alternating stresses on those parts of the structure which transmit them. In this case yield point, maximum strength, and ductility are not the determining factors since any plastic deformation afforded by ductility would inevitably affect alignment of the main bearings or otherwise distort the structure—a very small amount perhaps, but yet sufficient to interfere with the correct functioning of the engine.

The factor controlling endurance life in such an instance of loading is the fatigue limit of the weakest part and if, as has been shown, one type of weld is all-round inferior to another type, the production engineer will be guided in his choice by his knowledge of the strict requirements of the case and will not be influenced by the lower production costs of the former.

There are, of course, innumerable instances of welded application where welding is not required to develop great strength and where single run welds adequately meet the requirements of the work in hand. In such cases it is possible by adopting certain methods to speed up the rate of production enormously.

Another important factor which affects weld efficiency is the contour of the joint. Whenever a structure which includes change of section is stressed the stresses will be at a maximum wherever the sharpest change occurs and it can be shown that the general contour of the weld results in concentrations of stress, the values of which may exceed the average stress of the section by many times. For this reason such welding defects as undercutting and lack of root penetration are strongly to be condemned. These two defects probably are responsible for more failures in electric welding than any other cause. Undercutting is due to errors of operation and constitutes a definite line of weakness, since the high concentration of stress around the groove thus formed is located at that zone in the plate already weakened by grain growth resultant upon overheating. The effect of such conditions under steady load may not be serious if the ductility of the weld metal is sufficient to afford relief but, under working conditions of alternating stress they can only be fatal to the useful life of the connection.

Lack of root penetration is the defect primarily responsible for the cracking of welds either in the making or in subsequent service.

Here again the high stress set up round the notch left by the unwelded area in association with the contractional stress of the cooling weld metal provide an initial fracture which may extend through the section of the weld during the cooling period or may be hidden internally until it causes failure when the structure is loaded.

It has been shown by Everett Chapman and other investigators that the stress conditions affecting contour and the defects mentioned can be simulated by examining a piece of stressed bakelite under polarised light.

The remaining efficiency factor of a welded joint is the value of internal stress left in the structure consequent upon contraction of the weld metal. The magnitude of such stresses vary considerably with the rigidity of the structure. The exact nature of internal stress is not yet well understood and appears to be outside the control of the operator. The practice in America for some time past has been to stress relieve, by low temperature annealing, structures such as pressure vessels with high working pressure and this practice is gradually being adopted in this country. The treatment consist of passing the vessel or assembly into the furnace on a moving platform and heating to a temperature of 600 degrees C. for an hour for each inch of maximum thickness. In this way it is believed that residual stresses are reduced to a minimum if not entirely eliminated. On certain classes of work and all welding carried out in situ, heat treatment of the kind described is impracticable, but experience shows that if suitable factors of safety are applied no undue anxiety need be felt on the score of residual stress.

Procedure Control.

There is but little doubt that in the past the bulk of commercial welding has been done in an haphazard and empirical manner, perhaps due to the general impression among engineers that the process is an art that could only be carried out by skilled craftsmen. There appears, however, to be no reason why welding on ordinary production should not be reduced to a science under definite and complete control in the same way as any other industrial science. Such a procedure control would be one whereby a weld of a given standard of size and strength can always be reproduced under standard conditions. Providing certain conditions are complied with, the only variable factor is the welder. According to the system suggested the welder should be trained on a minimum number of types of electrodes suitable for the class of work upon which he is to be engaged. The training should consist of acquiring the ability to deposit a given gauge of electrode in a given length of run with a given current value. When this proficiency has been gained all variables are disposed of and all welds made in the same way should be identical in character and strength. Such a procedure would

prescribe for all the factors governing efficiency as determined by preliminary trial welds and in addition would provide an accurate check to the cost of work in progress and a quick reliable means of estimating. The exact procedure for a certain type of weld can be determined by making trial welds in various ways and testing them until the requirements of the welding to be carried out are satisfied. Once data for a given weld is established it could be given a symbol and quoted on drawings when a weld of similar size and strength was required.

It is now generally agreed that non-destructive testing of welds is not economically possible. While the X-ray method provides an excellent means of determining the general soundness of a weld the cost of such inspection would be prohibitive for the ordinary run of work. The compromise of taking radio photographs here and there at random is quite unsatisfactory since the area containing a flaw may be the one that is missed. It seems then that the way to ensure commercially sound welding is to adhere to a system such as that described and maintain supervision by visual examination.

In order to exploit fully the advantages of procedure control all welds, as far as is practicable, should be made in the downhand position even if it means installing the necessary handling appliances. Vertical and overhead welds are difficult to make calling for much greater skill on the part of the operator ; they are expensive to produce since only relatively small electrodes and low current values are suitable for their execution and they are less efficient than those made downhand. Large fillets between horizontal and vertical components are notoriously difficult to make. They have to be built up with a number of relatively small runs to preserve any semblance of contour and only an expert can avoid undercutting the vertical member. These difficulties vanish when the structure is tilted to the horizontal and a much superior weld can be produced at half the time and cost.

For some time past there has been a growing tendency in this country to follow the lead of America in the use of much larger electrodes than those hitherto employed and a few firms are now using electrodes up to $\frac{3}{8}$-inch diameter and over with satisfactory results. It has been shown that a single run deposit produced with large diameter electrodes and high current values is in no way inferior to that resulting from smaller electrodes with appropriate current ; in fact evidence points to the fact that they are sounder and neater.

Speed weldings naturally offers attraction to production, but experimental work to date dictates caution against their indiscriminate application. For instance, by employing suitable preparation of the plate edges a $\frac{3}{8}$-inch butt seam may be welded with a $\frac{5}{16}$-inch diameter electrode at a speed of 43 feet per hour and develop

adequate efficiency for a certain class of work. Root penetration is not completely effected, yet no cracking follows the procedure. This may seem contradictory to what has already been said in connection with the cause of cracking, but it should be remembered that in this case the high current used and the thickness of the plate, results in greater heat distribution and therefore greater ductility to relieve stress concentration. To use the same gauge of electrode for the first run of a seam of heavy section would be decidedly risky and definitely is not recommended. Recent experiments by the writer show that with electrodes over No. 4 gauge root penetration is not obtained on fillets, no matter what current value is applied : while No. 6 appears to be the minimum for 60 degrees close butted joints. The writer would much prefer No. 9 gauge to be on the safe side. All this points to the wisdom of the course suggested ; that the production engineer should, himself, predetermine by trial all the data necessary to enable him to evolve a procedure suitable to his own particular class of work.

Discussion.

MR. J. G. YOUNG (Chairman) said that after the considerable research work put into it, welding was fast becoming a highly scientific operation. There was room, of course, for a good deal more educational work, and he had not the least doubt that in the long run the operation of welding would be acknowledged as a scientific art in keeping with its importance in engineering. He would like some information concerning the liquid oxygen welding process, of which there was a good deal done in Sheffield for breakages, and hard surfacing.

MR. KENNARD replied that he had had no experience of the liquid oxygen process of welding. Most of his experience had been applied to acetylene and electric welding—almost wholly electric in the last fourteen years. With regard to hard surfacing, some progress has been made in that direction quite recently. Until a year or so ago there were other processes, but recently an electrode has been evolved consisting of mild steel spiral winding, and a flex, which has made it possible to introduce the operation in a convenient form. Hard surfacing was being used extensively for machinery in connection with the well boring in the oilfields.

MR. MARTIN said that the lecturer and himself used to be welders with fixed notions about certain things. Now, however, Mr. Kennard appeared to be advocating the adoption of depositing electrodes in a way different to that in which they were deposited a few years ago. Speaking of undercutting in welding, this was due to bad operation, and Mr. Kennard was blaming the welder, but he ought not to do so. Undercutting was due to one of two things—excessive current strength or using electrodes not suitable for the job.

MR. KENNARD : I am compelled to agree with Mr. Martin, up to a point, in his comments about undercutting, but if you are not going to blame the welder you must blame the production engineer. Most of us know that electric welding was looked upon in the past as a sort of putting-on tool—as a convenience for getting over a difficulty. Now it is an acknowledged process, and it has to be treated scientifically. If the production engineer specifies the wrong current value and that results in undercutting you cannot blame the welder, but if you leave it to the welder he has to call upon the fruits of his experience. Referring to procedure control mentioned in the paper, I did not say that welds had to be made by moving straight along the seam without sideways movement. It is merely a question of practice on the part of the operator. Until quite recently we have not endeavoured to control our own welding, but we felt we were being pushed a little bit. We were being asked for figures and data and how many we could do in a certain time. Thus we had to do

something. It all boils down to the production engineer making his trial welds. He will discover what he can do, and discover which is the better way to make the weld, and once he obtains that data he can use it for all future weldings.

MR. NURRISH raised a point about spot welding between two electrodes of the thinner gauge metals. He mentioned that his firm had occasion some time ago to electrically weld some chromium steel which had a chromium content of 22 per cent. An apparently perfect weld resulted, and they made many tests. Subsequently in the repeated operation of heating and cooling the two pieces dropped apart. There was, in fact, no effective weld after heating and cooling two or three times. There was also the question of the methods of electric welding of non-ferrous objects.

MR. KENNARD replied that he had no information about spot welding. As regarded non-ferrous welds, nothing like the same degree of efficiency was obtained from non-ferrous methods as on mild steel by the electric process. Copper could be welded by the electric method but with nothing like the same efficiency as by the acetylene method. He referred this point to Mr. Martin, whom he described as the biggest authority in the country on the subject of copper welding.

MR. MARTIN: As a matter of fact, copper welding can be quite well done electrically. No one appears to be interested in copper welding, and they are not prepared to carry out experimental work to find out more about it. The result is that no one can know very much about copper welding. Referring to the question of the spot welding of 22 per cent. chromium steel, Mr. Martin said the trouble there was the fact that they heated the steel to a higher temperature than it could stand. It probably made a good weld to the chromium, but there were serious difficulties in this chromium steel electric welding, and he should prefer the welding operation in this case by the acetylene process.

MR. R. J. MITCHELL said he feared that Mr. Kennard in giving his hearers the benefit of the thorough practical knowledge which he possessed of the subject of welding in so many of its varied phases, assumed that the members of his audience knew more than they really did of the fundamentals. Mr. Kennard did not refer in his paper to the possibilities of mechanising electric welding. Could Mr. Kennard enlighten them as to the relative methods of A.C. and D.C. welding?

MR. KENNARD said A.C. welding could be an equally efficient and satisfactory operation as that of a D.C. method. Certain types of electrodes in the D.C. operation produced smoother welds than with A.C., and with the D.C. also the use of bare wire was quite possible if there were those old fashioned enough to do so, whereas A.C.

presented certain difficulties. With a well designed transformer it was quite possible to weld with bare wire in the overhead position.

After MR. H. C. NEWELL and the chairman had raised further points, MR. KENNARD speaking on the question of the covering of electrodes, said they would have to judge the pudding by the eating. The tendency recently had been to apply a covering for the electrode which functioned on a rather different principle to the more orthodox type. Speaking of continental experiences, where welding was concerned the United Kingdon was an " also ran " with many other countries such as Germany, Austria, and the U.S.A. He held that there was a strong argument in favour of training welders on scientific lines. Doubtless there were many institutions up and down the country where facilities could be provided for the training of welders. It would be a most admirable scheme, and whether desirable or otherwise for mechanical reasons he could not help but feel that the welder should be classified according to his skill.

The meeting concluded with a cordial vote of thanks to the lecturer.